ELECTRIC DIESEL PARTICULATE FILTER DEMONSTRATION

by

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ABSTRACT

A diesel particulate filter (DPF) is highly effective at removing particulate matter (PM) from the exhaust stream. Removing the collected soot (i.e., regenerating the filter) is a more challenging problem, and for this reason a large number of diesel engines are not compatible with currently ARB-verified DPFs. This includes many older engines found in school buses.

The objective of Cleaire's ICAT project was to develop and demonstrate a product that decouples the regeneration from the engine's operating conditions through off-line electrical heating of the DPF. The ICAT project's goals were to optimize the hardware, control systems, and operational procedures to create a robust and fail safe PM control system that can be used in widespread duty cycles and on older engines.

The Horizon EPF and regenerative infrastructure performed as designed during the ICAT project and field demonstration. The chassis dynamometer testing validated the Level 3 emission reduction goal for the EPF (greater than 85% PM removal efficiency). Furthermore, the testing found that the Horizon EPF reduced the NO_2 emissions, thus providing an additional air quality benefit. Cleaire successfully met the objectives of the ICAT project and is now commercializing the Horizon EPF product.

EXECUTIVE SUMMARY

Cleaire received an ICAT grant from the ARB to develop and demonstrate an electric particulate filter (EPF) for retrofit applications on in-use diesel engines. The primary objectives of the project were to develop a robust product, design and install the necessary regenerative infrastructure, demonstrate the technology in field trials and validate the emission performance in laboratory testing.

The ICAT project was comprised of five major tasks over a one-year time frame:

1. Build prototype and regeneration emissions testing
2. Installation of regenerative infrastructure
3. Installation of EPF on demonstration vehicles
4. Field testing of technology
5. Dynamometer emission testing, final report and technical seminar

Cleaire built and tested prototype systems before the ICAT project formally began and refined the product prior to the ICAT field demonstrations and testing. The six-month field trial on a school bus operated by the Elk Grove School District (Sacramento County) provided rigorous testing of the:

- components of the EPF system
- control system algorithm that notifies the user to plug in the system (a flashing amber light)
- operator's response to the flashing amber light (to plug in the system)
- design and operation of the regenerative infrastructure
- vehicle's typical operating range (no noticeable effect from the EPF)

The EPF system and regenerative infrastructure performed as designed. Furthermore, the school district was so pleased with the vehicle's operations and the EPF's performance that it purchased and installed a total of 49 systems.

The regeneration emission testing showed no adverse emissions during the regeneration process. The chassis dynamometer testing validated the greater than 85% PM removal by the EPF. Additionally, the dynamometer testing showed a high level of NO_2 reduction from the EPF allowing it to meet Level 3+ performance.

Cleaire was able to use the ICAT project to validate that the EPF is a commercially ready Level 3+ device for wide-spread application on in-use diesel engines.

I. Introduction

The ICAT project accelerated the development and commercialization of the Horizon EPF. Details of the product development, field demonstration and test results have been submitted to the ARB in various reports over the course of the project. The tasks, goals and results are summarized in this final report, which completes the ICAT project.

II. Innovative Technology

System Description

The EPF is an emission control system that captures particulate matter emitted from an operating engine at efficiency rates above 85%. The EPF consists of an uncatalyzed silicon carbide (SiC) wall-flow diesel particulate filter, an electric heating element, an air pump, and electronic controls. The EPF replaces the existing muffler, and offers sound attenuation equal to or better than the original muffler. The electronic control system monitors exhaust backpressure and manages the regeneration process.

All necessary hardware and controls are installed on the vehicle, requiring only off-board electric power to supply energy for the heater. When the amber LED flashes and the vehicle is parked for a period that will exceed five hours, the operator plugs the power-supply station receptacle into the EPF's power plug located on the vehicle. A starter lock-out is engaged when the system is plugged into AC power to prevent the vehicle from being started and operated while it is plugged in. The basic system schematic is shown in Figure 1.

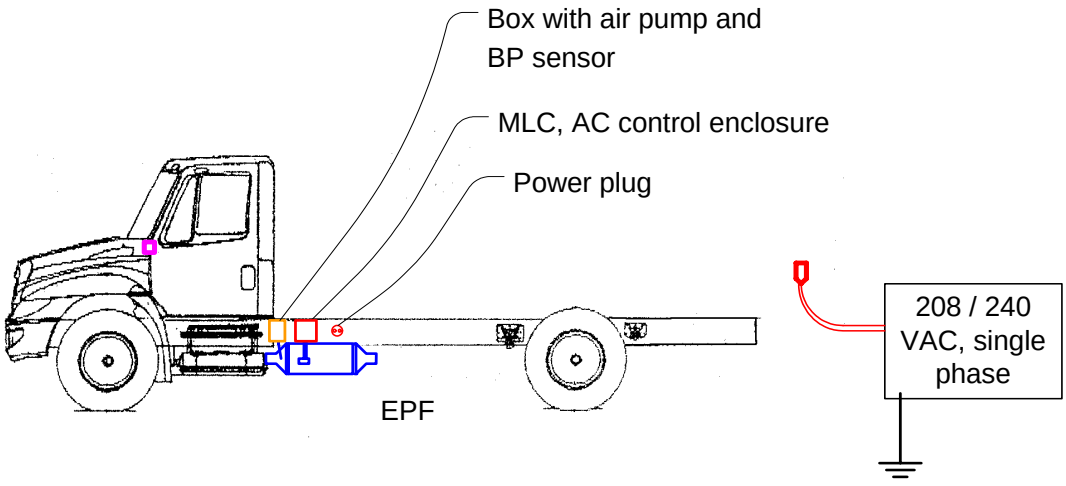

Figure 1. EPF system schematic.

PM Filter

The EPF uses a commercially available wall-flow silicon carbide filter to capture and hold PM emitted from a diesel engine. The filtration efficiency of these filters has been extensively documented and the filters have repeatedly achieved Level 3 status in the test laboratory. The captured PM will accumulate in the filter over time as the engine is operated and must be removed or oxidized periodically (i.e., regenerated). Since the filter is uncatalyzed, fuel sulfur levels do not affect its particulate reduction performance, nor does it increase NO_2 emissions across the device (in fact, our dynamometer testing to date has shown *reductions* in NO_2 emissions).

Control System and Regeneration Process

The regeneration event is controlled by the on-board controller (MLC). The MLC indicates to the operator with a flashing amber light that a regeneration is requested based on exhaust backpressure measurements during engine operation. The regeneration is independent of any other filter conditions such as pre-heating from in-use operation. Regeneration of the EPF occurs while the engine is off and the system is connected to external grid power. The DPF is not removed from the vehicle for the regeneration process.

The regeneration process requires a heat source to raise the PM above its oxidation temperature and a source of air to allow for oxidation to occur. An electric heating element is used as the heat source and a small air pump is used to supply the air. The MLC controls the operation of these two devices.

Upon return to the designated parking space, the vehicle operator will connect the EPF to external grid power (208/240-volt single-phase AC). If needed, as indicated by the flashing amber light, the MLC will allow current to flow through the resistive heating element. Through convection, conduction and radiation, heat is transferred to the filter substrate, bringing it to a temperature necessary to combust or “burn-off” the captured PM. The entire regeneration process lasts five hours and is anticipated to occur at off-peak hours such as late evening or at night.

As with any filter system, non-combustible inorganic ash will need to be removed periodically. We anticipate that the de-ash process will be a necessary part of an annual maintenance cycle. However, more frequent de-ashing may be necessary depending on the specific engine (and its oil consumption rate) on which the EPF is installed.

Technical Innovations

The EPF’s regeneration process is “active on-board, off-line” regeneration (in contrast to the typical catalyzed filter which can be classified as “passive on-board, on-line” regeneration). By decoupling filter regeneration from the vehicle’s duty cycle, a much broader range of applications is possible for wall-flow PM filter technology.

Furthermore, Cleaire’s MLC provides a robust control system that can not only monitor the system and control the regeneration, but provides a simple interface with the driver or operator as well as detailed data logging and diagnostic capabilities for trained Cleaire-authorized technicians.

Transforming these concepts for technical innovation into a robust product that works in real-world applications with typical operators was the main challenge and achievement of the ICAT project.

III. ICAT Project

Cleaire had a number of objectives for the ICAT project. This section reviews the objectives and compares them with the outcomes from the ICAT project. Cleaire also performed EPF product development and verification efforts concurrently with (but outside the scope of) the ICAT project. Those results are also included in this report where appropriate.

Task 1. Build prototype and regeneration emissions testing

Cleaire performed extensive R&D testing of prototype systems. Based on the development test results, the regeneration system, heaters and other system components were modified for the ICAT field trial system.

The development testing including testing various soot loadings in the filter before regenerating and measuring temperature profiles in the filter. Emissions during the regeneration process were measured at an emissions testing facility and the test results were submitted to the ARB for the ICAT project. Part of the challenge of testing regeneration emissions was that an approved protocol did not exist. Cleaire developed a protocol and provided it to the ARB for review and acceptance. The end result of the testing is that regeneration emissions are negligible, especially when compared to the high rate of PM removal from the Horizon EPF or to the emissions of an operating engine.

Simultaneously with the ICAT project, Cleaire was performing field trials for a customer who wishes to remain unnamed. Based on operating experiences from ICAT and the other field trials, the commercial Horizon EPF system had a few additional minor modifications from the ICAT prototype systems.

Task 2. Installation of Regenerative Infrastructure

Cleaire created specifications for the regeneration infrastructure. The field trials showed that each facility has its own limitations on power availability and its own needs regarding placement of the power-supply station. It is the responsibility of the customer and their electrical contractor to choose an infrastructure design that will conform with local codes. Nonetheless, Cleaire has worked with them to ensure that a safe and effective regeneration infrastructure is installed.

Sacramento Municipal Utility District (SMUD) installed power-supply stations (regenerative infrastructure) at their cost for Elk Grove USD as part of the ICAT project. The power-supply stations have been successfully operating as designed.

Task 3. Installation of EPF on demonstration vehicles

Cleaire installed a Horizon EPF system on a Thomas Built school bus owned by Elk Grove USD (Sacramento County). This was the primary ICAT demonstration vehicle. The bus had been repowered with a 2004 Cummins ISB prior to installation of the Horizon EPF. The results of the demonstration are discussed in Task 4.

Concurrently but outside the scope of the ICAT project, Cleaire installed and demonstrated the EPF on a Cummins West delivery vehicle with a 1988 engine and some utility vehicles operated by a customer that chooses to remain unnamed.

Originally, Cleaire had planned to install the EPF on a mid-1970s vintage Crown school bus owned by Grant Joint Union School District. However, this installation did not occur for the ICAT project due to the configuration of the vehicle exhaust system and approval of the installation by the California Highway Patrol. Normally, the EPF would directly replace the existing engine muffler, but due to the mid-engine design of the Crown school bus, the existing muffler location was incompatible with the EPF's mounting requirements. An alternative location on the vehicle was identified and a support bracket designed, but the approval by the CHP was not obtained in time to use this vehicle for the ICAT project. Cleaire has since streamlined the approval process with the CHP and has received approval for installation on a variety of school bus body styles and engines including a 1959 Crown school bus.

Task 4. Field testing of technology

The Horizon installed on the Elk Grove school bus performed as designed during the ICAT demonstration. Cleaire submitted reports to the ARB for the first three months and the second three months of the ICAT demonstration. Elk Grove USD was so pleased with their ICAT demonstration unit that they purchased and installed a total of 49 Horizon EPF systems.

Concurrently, but outside the scope of the ICAT project, Cleaire demonstrated and tested the EPF on a Cummins West delivery vehicle with a 1988 engine and some utility vehicles operated by a customer that chooses to remain unnamed. A report of the extreme testing on the Cummins West vehicle was submitted to the ARB. The testing demonstrated that the Horizon EPF product is robust and the control system is properly calibrated to alert the operator to plug in the EPF with plenty of time to spare.

Task 5. Dynamometer emissions testing, final report and technical seminar

California Truck Testing Services (CaTTS) performed emissions testing on February 13, 2006 of the EPF's PM filter used during the ICAT demonstration. (The baseline tests had been performed on January 20 and January 25.) The Urban Dynamometer Driving Schedule (UDDS) and the New York Bus (NYB) test cycles were used to measure the EPF's emission reduction performance.

The EPF achieved greater than 85% PM removal efficiency for both test cycles which was the emission reduction goal of the ICAT project. The EPF also *reduced* NO_2 emissions by a significant amount. The test results are shown below in Table 1. A complete test report was submitted to the ARB.

Table 1. Emissions test results of key gaseous pollutants and PM. Note: All results in g/mi

CaTTS #	Test	Configuration	THC	CO	NO_x	NO_2	CO_2	PM
C0601051	UDDS	Baseline	0.672	3.889	18.53	1.596	2148	0.394
C0601052	UDDS	Baseline	0.646	3.698	17.61	1.655	2144	0.372
C0601053	UDDS	Baseline	0.632	3.786	17.85	1.650	2160	0.400
		Average, Baseline	**0.650**	**3.791**	**17.99**	**1.634**	**2151**	**0.389**
C0602039	UDDS	EPF #7	0.570	5.112	18.58	0.186	2228	0.036
C0602040	UDDS	EPF #7	0.350	5.110	19.08	0.423	2220	0.033
C0602041	UDDS	EPF #7	0.404	5.080	18.42	0.515	2216	0.038
		Average, with device	**0.441**	**5.101**	**18.69**	**0.375**	**2221**	**0.036**
		Effect of Device	**-32.1%**	**34.5%**	**3.9%**	**-77.0%**	**3.3%**	**-90.8%**
C0601068	NYB	Baseline	3.335	14.23	39.90	3.895	4915	1.270
C0601069	NYB	Baseline	2.583	14.41	38.77	3.311	5015	1.287
C0601070	NYB	Baseline	2.467	14.96	37.86	2.603	4920	1.356
		Average, Baseline	**2.795**	**14.53**	**38.85**	**3.270**	**4950**	**1.304**
C0602043	NYB	EPF #7	0.188	15.84	38.05	0.931	4999	0.185
C0602044	NYB	EPF #7	1.715	15.84	37.44	0.000	4977	0.132
C0602045	NYB	EPF #7	1.568	15.56	37.05	0.021	4895	0.211
		Average, with device	**1.157**	**15.748**	**37.51**	**0.317**	**4957**	**0.176**
		Effect of Device	**-58.6%**	**8.4%**	**-3.4%**	**-90.3%**	**0.1%**	**-86.5%**

Cleaire held a technical seminar with the ARB on March 16, 2006. This final report completes Task 5 and the ICAT project.

IV. Status of the Technology

Cleaire submitted the ICAT pre-proposal for the EPF in the spring of 2004. That action began a series of events, which resulted in the Horizon EPF being developed, verified and commercialized sooner than Cleaire originally anticipated.

Cleaire received ARB verification of the Horizon EPF in December 2005. Cleaire is in the process of expanding the Horizon EPF verification for additional engine families and for minor part changes. Cleaire's distributor, Cummins West, is marketing the Horizon and is receiving positive response from a number of customers. Elk Grove USD was very pleased with the results of their ICAT demonstration. They have since purchased and installed a total of 49 Horizon EPF units.

Cleaire has envisioned a number of variants to expand the Horizon EPF product line to expand its applicability and provide greater operating flexibility to the customer. Cleaire has applied to the ARB for the 2006 ICAT solicitation for funding three of these projects.